

Raincube Mission: Results After One Year in Space

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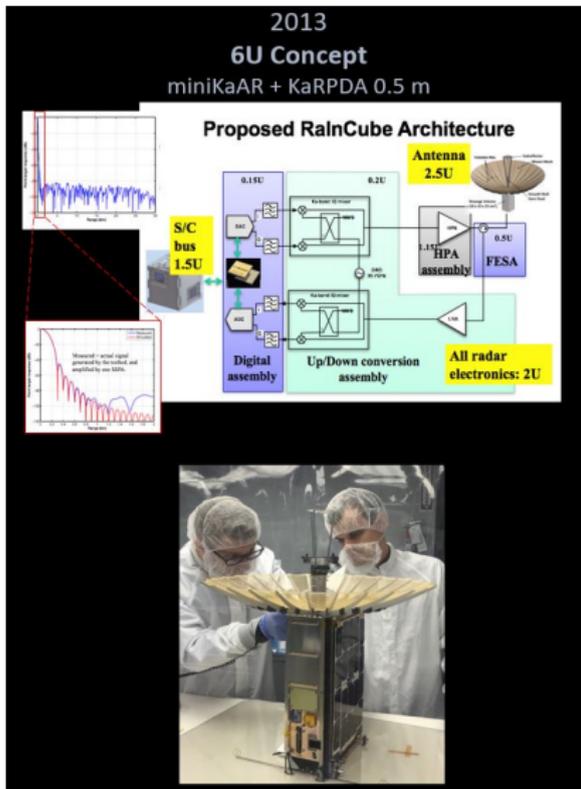
Radar Science & Engineering Section
Jet Propulsion Laboratory, California Institute of Technology

AGU Fall meeting

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December 5, 2019

1st Profiling Radar in a CubeSat: Dr. Eva Peral (PI, JPL)

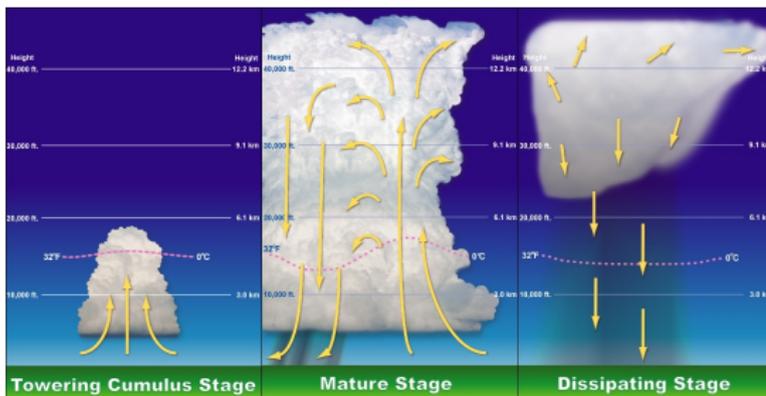


- NASA ESTO InVEST program
- NASA Earth Science Division's Flight and R&A Programs

Frequency	35.75 GHz
Antenna size	0.5 m
Volume	6U (10 × 20 × 30 cm ³)
Mass	5.5 kg
RF Power	10 W
Processing	PC & Offset (I,Q) modul.
Beams	1 (nadir)
Hor. Resolution	8 km
Range Res	250 m

E. Peral et al., "Radar Technologies for Earth Remote Sensing From CubeSat Platforms," in *Proceedings of the IEEE*, vol. 106, no. 3, pp. 404-418, March 2018

Fleet of cloud & precipitation profiling radars



(Lifecycle of a thunder storm). Credit: NOAA

	Cloudsat (2006)	GPM (2014)
Max size/ weight	5.1 m/995 kg	13 m/3850 kg
Swath [km]	nadir	125–250
I_{orbit} [°]	98	65
Altitude [km]	705	407
Revisit time	~ 16 days	~ 3 hours

single-cell

30 mins

multi-cell

few hours

GEO

challenging

LEO

constellation

Radar in a CubeSat: PI Dr. Eva Peral, radar/JPL

2013
6U Concept
miniKaAR + KaRPDA 0.5 m

Proposed RainCube Architecture

S/C bus 1.5U

Digital assembly 0.15U

Up/Down conversion assembly 0.2U

All radar electronics: 2U

Antenna 2.5U

FESA 0.5U

Measured - actual signal power (dB) vs. frequency (GHz) plot.

Measured - actual signal power (dB) vs. frequency (GHz) plot.

Photograph of the physical hardware in a cleanroom.

	RainCube
Frequency	35.75 GHz
Antenna size	0.5 m
Sensitivity	13 dBZ
Hor. Resolution	8 km
Range Res	250 m
Beams	1 (nadir)
RF Power	10 W
Processing	Pulse compression

Tech demo objectives

Can such a radar, in LEO (400 km),

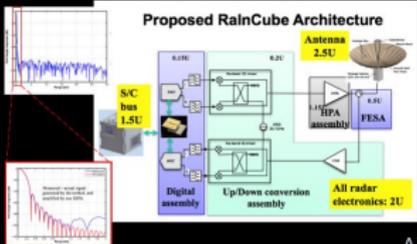
- detect precipitation?
- capture the vertical structure of storms?

RainCube: PI Eva Peral, radar/JPL, launch&ops/Tyvak

2013

6U Concept

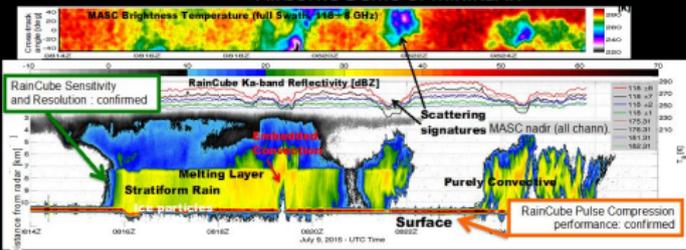
miniKaAR + KaRPDA 0.5 m



2015

PECAN

Airborne Demo of miniKaAR



May 2018

RainCube 6U
Launched to ISS



RainCube
○○○○●○○○

Pointing
○○

Deconvolution
○○○

ECMWF
○○

RC-NEXRAD
○○○

RC-GPM DPR
○○○

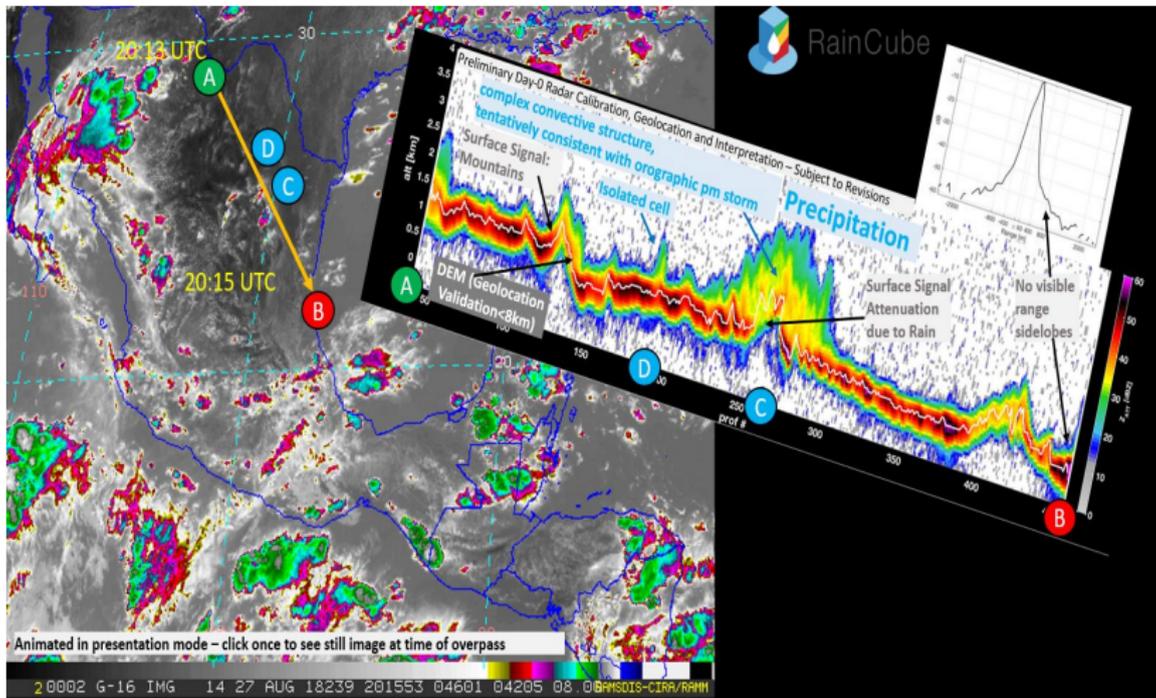
RC-Passive
○

Conclusions
○○○

Instrument

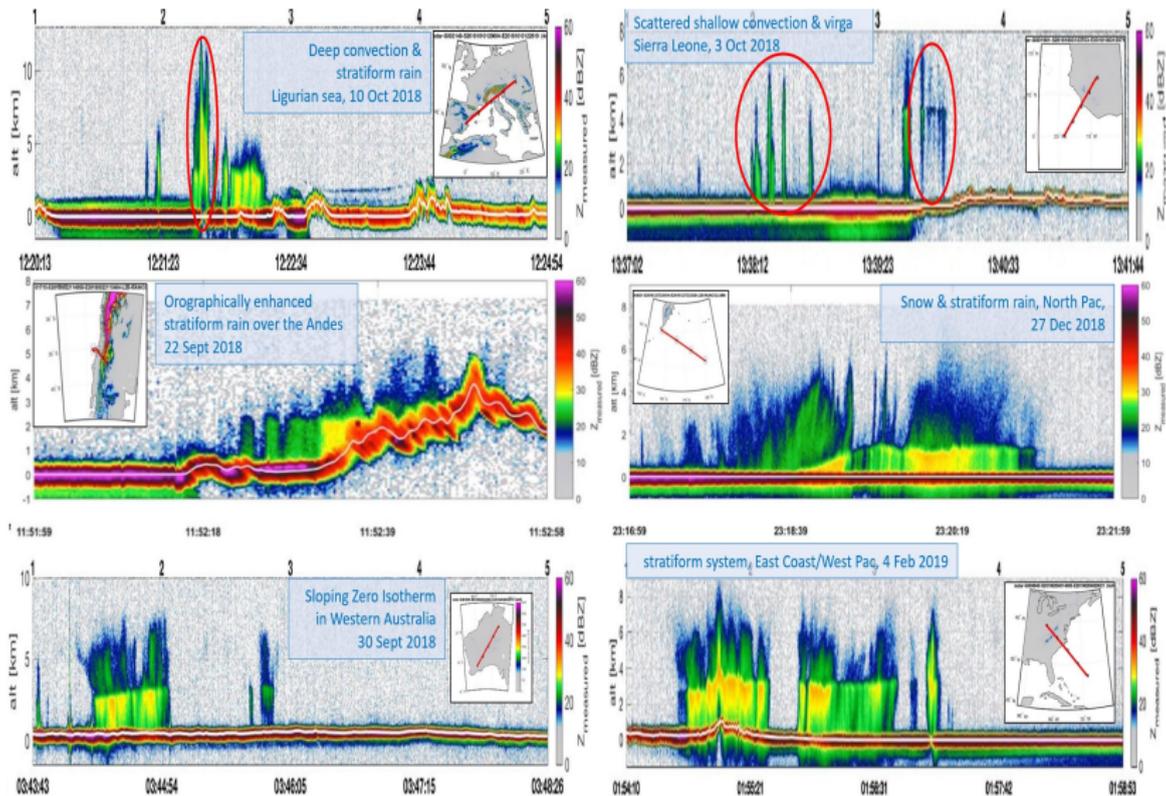
RainCube: PI Eva Peral, radar/JPL, launch&ops/Tyvak

1st detection of rain: 27 Aug 2018, Sierra Madre, Mexico



Fast growing orographic precipitation developed shortly before RainCube's pass

RainCube collection of storms (mostly from extended mission)



RainCube data hosted by TCIS portal

<https://tcis.jpl.nasa.gov/data/raincube/>

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TROPICAL CYCLONE INFORMATION SYSTEM

Welcome to the JPL Tropical Cyclone Information System

Introduction

The JPL Tropical Cyclone Information System (TCIS) was developed to support hurricane research. It has two components: a 12-year global archive of multi-sensor hurricane observations and, what was a near real-time portal, that supports the 2019 NASA Genesis and Rapid Intensification Processes (GRIP) hurricane field campaign. Together, data and visualizations from the near real time system and data archive can be used to study hurricane process, validate and improve models, and assist in developing new algorithms and data assimilation techniques. Below you will find links to various papers where you can view different types of data.

- Introduction
- Team
- Collaborators
- Funding
- Publications

Quantum Programs visit the U.S. Space & Ocean on Sunday, December 8, 2020. The secondary image (left) of the visualization was made by combining data from the infrared, microwave, and visible/near-infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) on the Advanced Very High Resolution Radiometer (AVHRR) satellite. The storm can also be seen with the advanced AVHRR (AVHRR) image.

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TCIS Data Repository

Here you will find data files from the JPL Tropical Cyclone Information System's Data Repository. Data may also be available from TCIS campaign portals. For additional information, please visit <https://tcis.jpl.nasa.gov>.

Name	Last Modified	Size	Description
PARENT_DIRECTORY	-	-	-
GRIP01	2019-08-01 19:07	-	-
GRIP02	2019-08-01 20:42	-	-
GRIP03	2019-09-11 12:17	-	-
GRIP04	2019-09-27 20:04	-	-
GRIP05	2019-10-09 12:00	-	-
GRIP06	2019-10-18 09:51	-	-
TCIS_DATA_ARCHIVE	2019-08-29 19:42	-	-

Data Distribution
#P5.1

Site Manager: Svetla M Hristova-Veleva

The Tropical Cyclone Information System hosts RainCube data.

Huge thank you to

PI : **Svetla Hristova-Veleva**,

Site Administrator: **Quoc Vu**,

Data Manager: **Brian Knosp**

L2A are posted (data & browse images).

L2B Data will be made public when QC is satisfactory.

No plan to open L0 and L1 data to the public.

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TROPICAL CYCLONE INFORMATION SYSTEM

Data from the RainCube Mission

For additional information, please visit <https://www.jpl.nasa.gov/ubsat/missions/raincube.jsp>.

Name	Last Modified	Size	Description
PARENT_DIRECTORY	-	-	-
zadar_004845_02190204014005_020193204020221_37A-GRIP06_v1.nc	2019-02-25 15:40	43K	
zadar_004845_02190204014005_020193204020221_37A-GRIP06_v1_new_bria_m02.jpg	2019-02-25 15:40	466K	

Overview

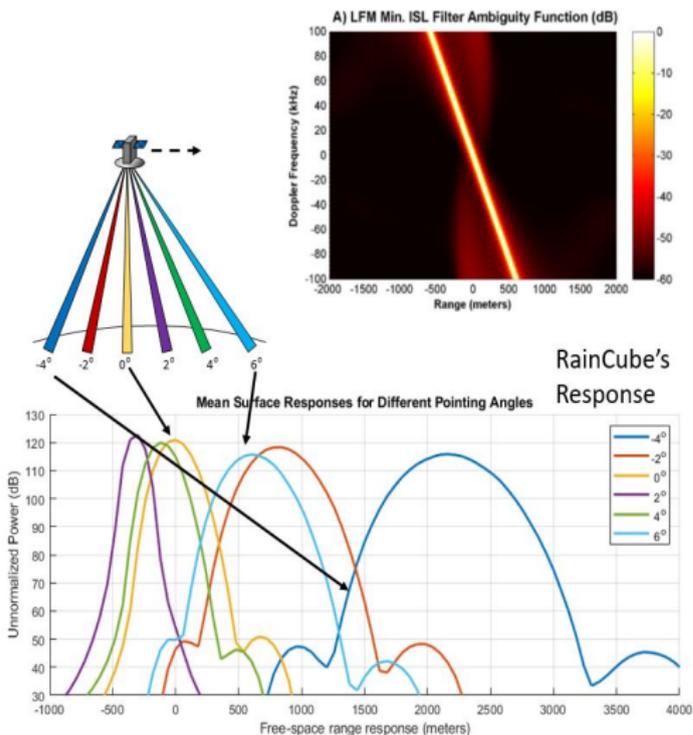
RainCube: Completed the Primary Objective of the Tech Demo

- ✓ detect rain from a 6U CubeSat
- ✓ measure the structure of storms from a 6U CubeSat

RainCube: additional objectives:

- RainCube data alone
 - ① Validate Pointing for geo-location
 - ② along-track deconvolution
- Environment from reanalysis (ECMWF)
- Calibration and Validation
 - ① NEXRAD
 - ② GPM DPR
 - ③ Combined Active-Passive

Flat Surface Response method



Occasional pointing drifts of platform

The Doppler shift from the surface
 ⇒ apparent shift in the range
 ⇒ broadening of surface response

Advanced modeling predicted that the apparent **pointing offset due to Doppler effects** should be $\sim 2.24^\circ$ forward for RainCube

R.M. Beauchamp, S. Tanelli, E. Peral, V. Chandrasekar, "Pulse Compression Waveform and Filter Optimization for Spaceborne Cloud and Precipitation Radar,"

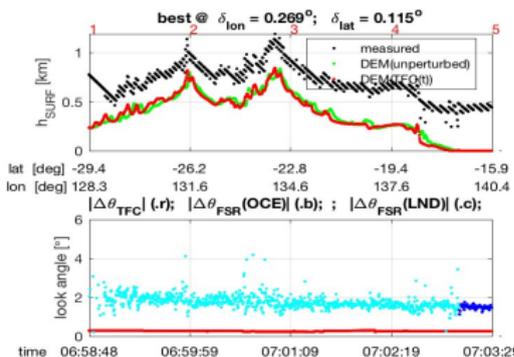
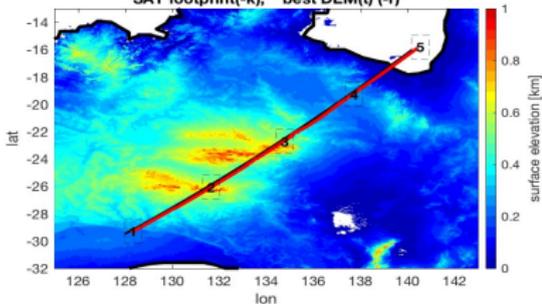
in *IEEE TGRS*, vol. 55, no. 2, pp. 915-931, Feb. 2017.

Topographic feature correlation (TFC) method

radar-telemetry-G001686-S20180921065851-E20180921070332.nc

2018/9/21 @ 6:58:49 --> 2018/9/21 @ 7:30

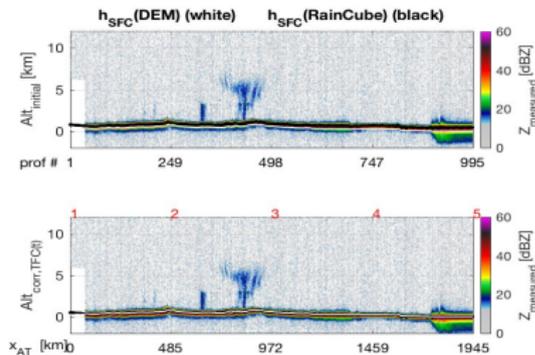
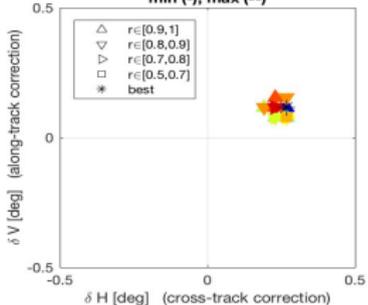
SAT footprint(-k), best DEM(t) (-r)



circles = range (from FSR) of $\Delta\theta$:

ocean (red); land (black)

min (-); max (-)



✓ unambiguous estimation of pointing angle

Deconvolution

- 8 km footprint sampled every 2 km along track
- Wiener deconvolution
- experimental
- tested on airborne data measured by JPL's APR-3 (Airborne Precipitation Radar), during CAMP²EX (NASA, Aug.-Oct. 2019, The Philippines)

RC-deconvolution (8 km footprint, ~1.9 km sampling, West Pac, 7 Sept. 2019)

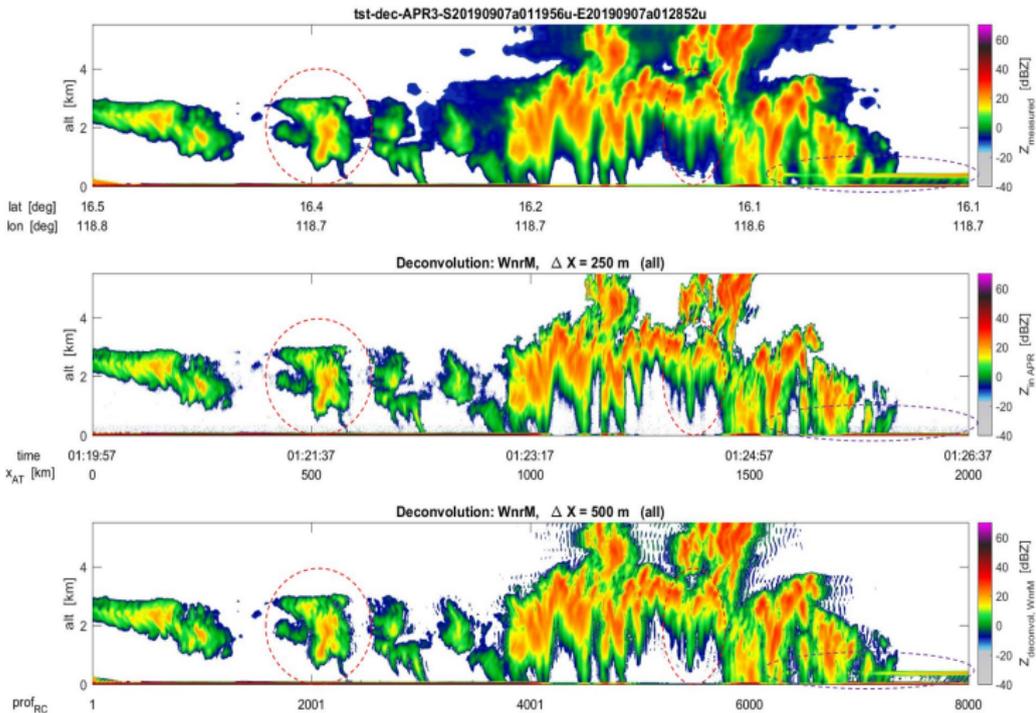


convolved by RC

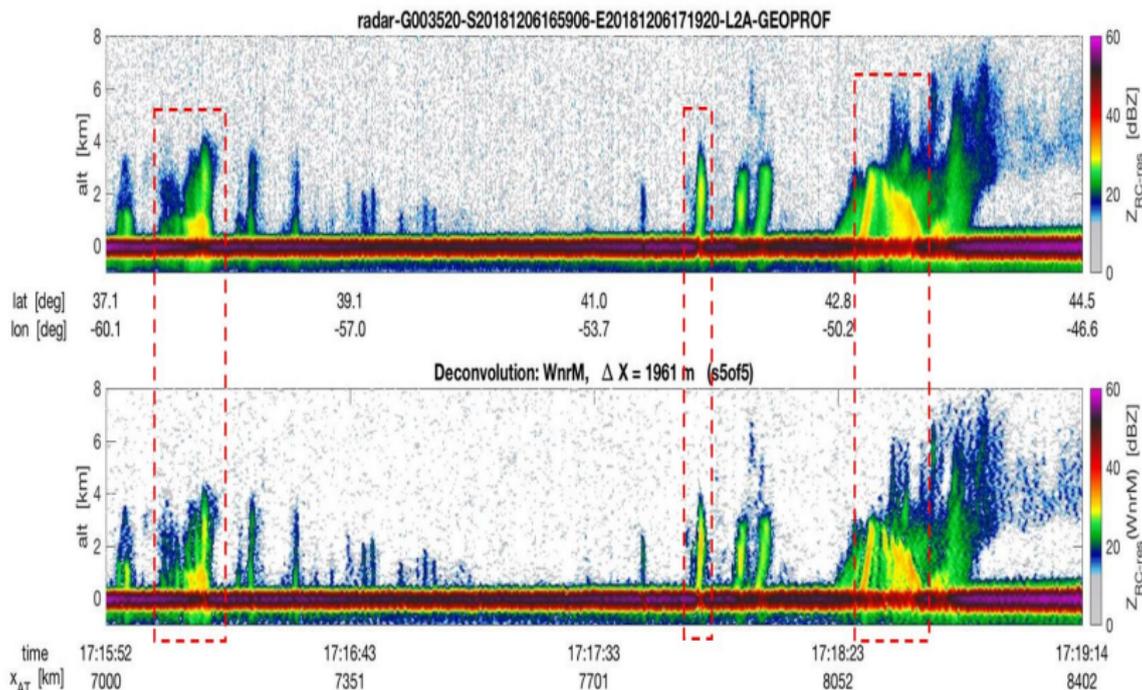
input original

deconvolved

sharper
↘ of SFC clutter
ringing



RainCube-deconvolution (8 km footprint, ~ 1.9 km sampling, N. Atlantic)

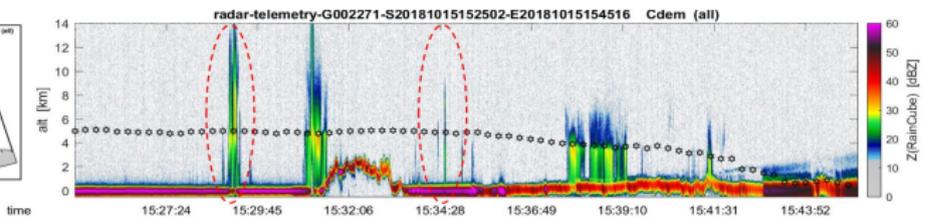
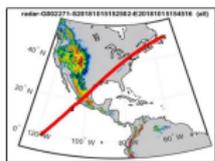


✓ sharper features, better resolution (*experimental*)

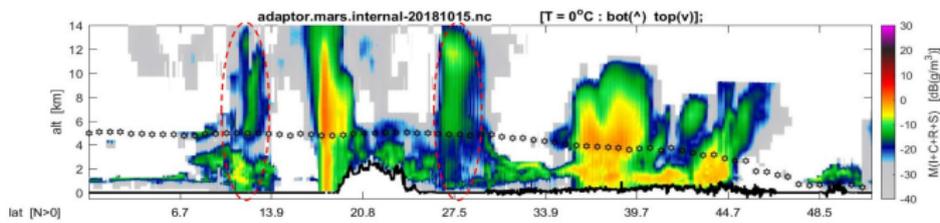
Reanalysis

- ECMWF ERA5 data
- hourly
- spatial resolution $0.25^\circ \times 0.25^\circ$ horizontally, 137 vertical layers
- state variables (T)
- Condensed water (Rain, Snow, Ice, Cloud liquid water)
- Note: Similar work done with NASA MERRA (3-hourly)

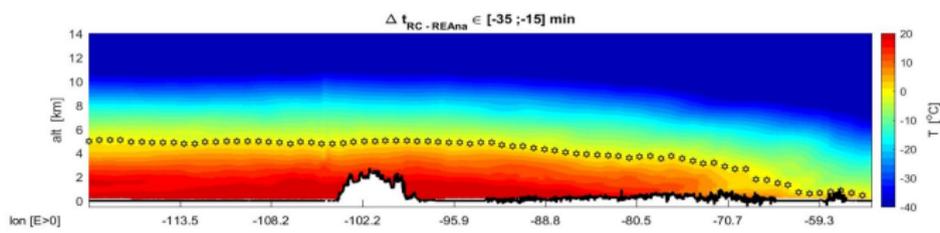
Storms in their environment (ECMWF ERA5)



$Z(\text{RainCube})$



M_{ECMWF}



$T_{\text{°C}}$

✓ general context (T) from reanalysis, but caution with M

RainCube & NEXRAD (Next-Generation Radar)

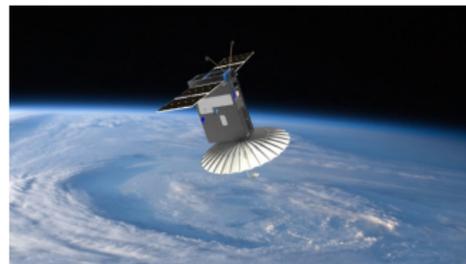
- National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA)
<https://www.roc.noaa.gov/WSR88D>
- S-band (2.8 GHz) data every 5-10 mins
- resampled to a $2 \times 2 \times 0.25 \text{ km}^3$ resolution



COMPLETED WSR-88D INSTALLATIONS
WITHIN THE CONTIGUOUS U.S.

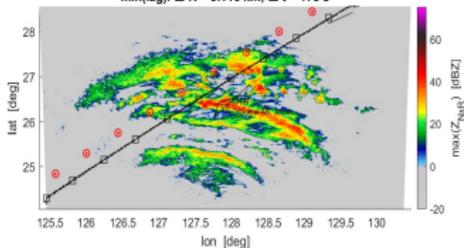


COMPLETED WSR-88D INSTALLATIONS

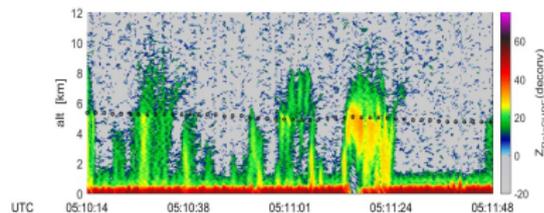
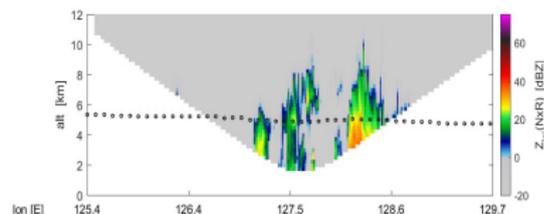
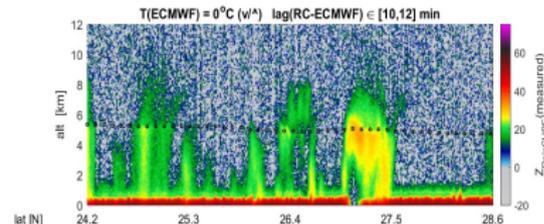
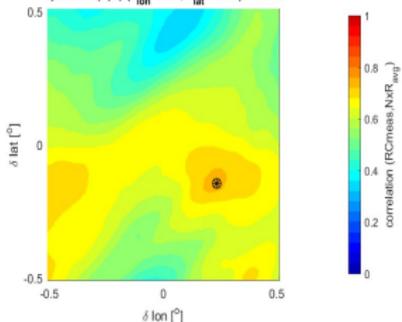


Co-location to NEXRAD (intended for rain rate retrievals)

RC(., o) radar-telemetry-G001997-S20181004050003-E20181004052017
 NxR: RODN - Kadena AB, Japan; profs(2km) (squares), profs(RC res) (-)
 min(dist): $\Delta R = 0.090$ km; $\Delta t = 255$ s
 min(lag): $\Delta R = 9.116$ km; $\Delta t = 173$ s



optimum (o): $\rho(\delta_{lon} = 0.24, \delta_{lat} = -0.15) = 73\%$

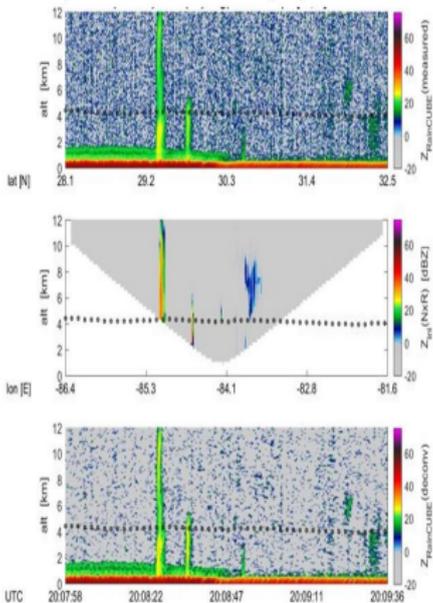


Complementarity

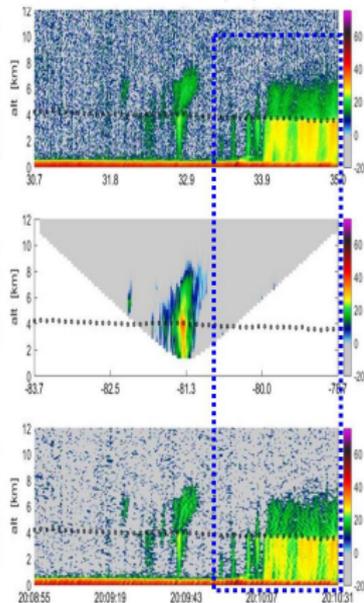
≠ viewing geometries, ≠ frequencies

Co-location to NEXRAD (dense coverage of CONUS)

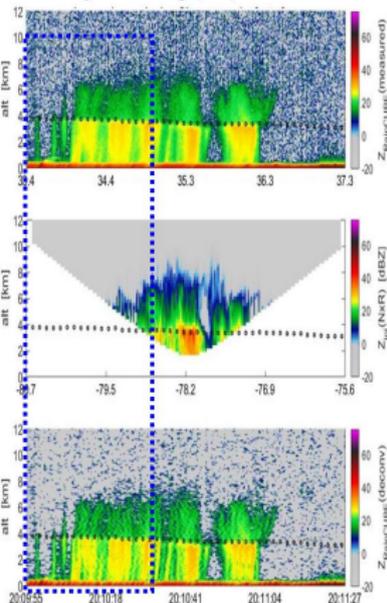
Deep convection: Tallahassee, FL, 1 Dec. 2018



Convection: Charleston, SC, 1 Dec. 2018



Stratiform: Raleigh, NC, 1 Dec. 2018



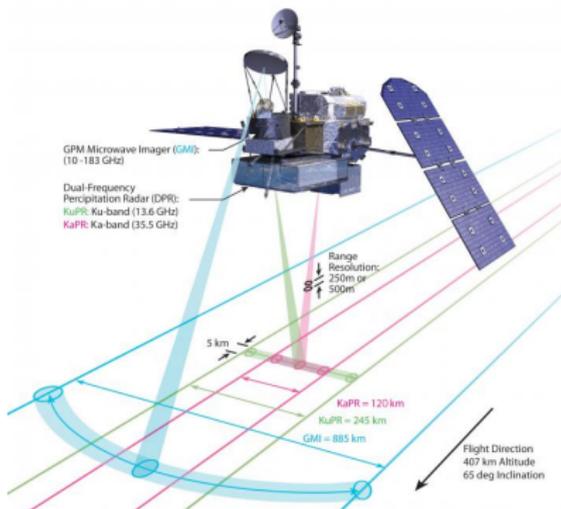
Complementarity

≠ viewing geometries, ≠ frequencies

GPM DPR

- Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR)
- NASA/JAXA

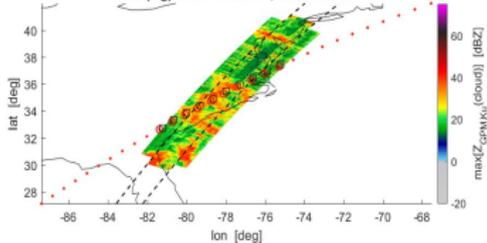
<https://pmm.nasa.gov/gpm>



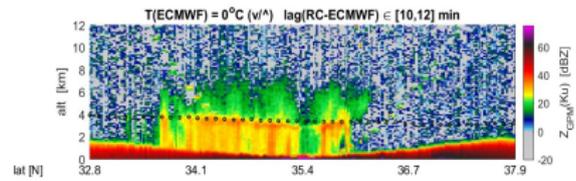
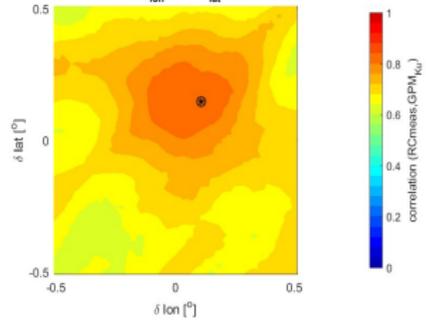
Approach

RainCube-GPM/DPR (NASA/JAXA, 03:14:40, E. Canada)

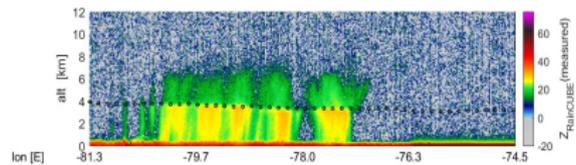
RC(., o) radar-telemetry-G003404-S20181201200107-E20181201202118
 GPM: granule 27040; footprints (squares), Ka swath (-)
 min(dist): $\Delta R = 0.091$ km; $\Delta t = 1801$ s
 min(lag): $\Delta R = 2.847$ km; $\Delta t = 1800$ s



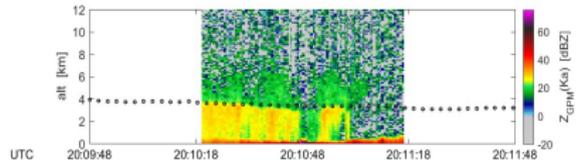
optimum (o): $\rho(\delta_{lon}, \delta_{lat}) = 0.11, \delta_{lat} = 0.15 = 84\%$



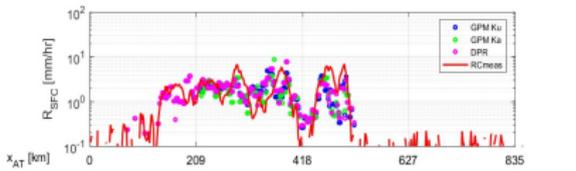
GPM(Ku)



RainCube

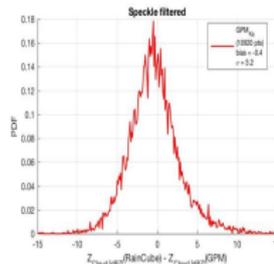
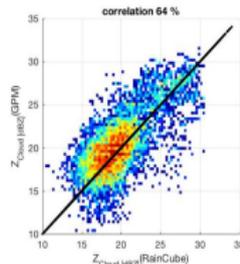
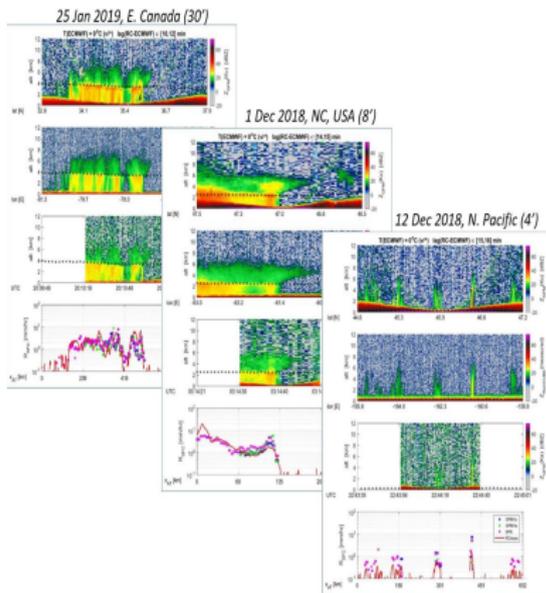


GPM(Ka)



R_SFRC

RainCube vs GPM/DPR-relative calibration validation



Bias RainCube vs DPR Ka

- $|Bias| < 1.5$ dB
- $|Bias| \ll \sigma$

Outcomes:

→ no calibration correction planned for next public release of science data

→ inclusion of this assessment in the product document for user awareness

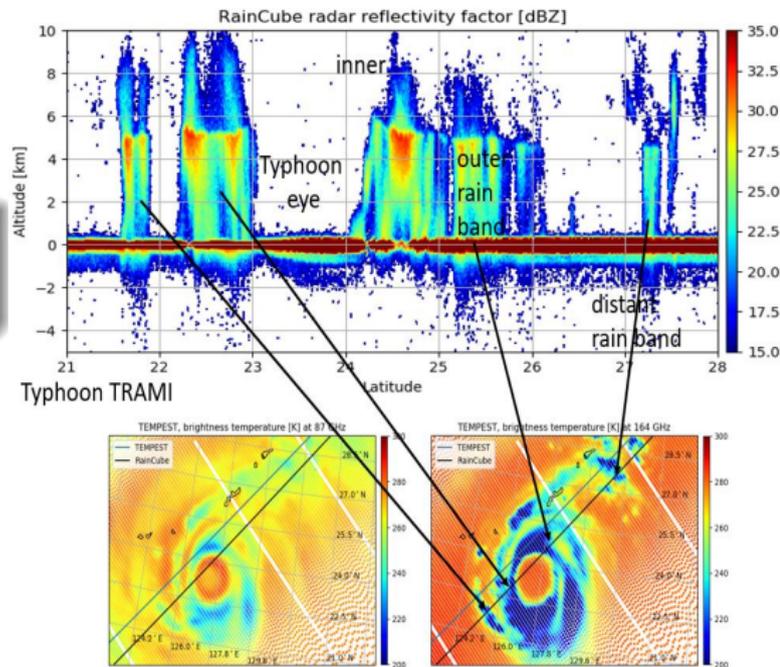
Storm Properties from Active & Passive

2 radar-radiometer datasets

- RainCube + TEMPEST-D
- RainCube + GPM

Engaged GPM Science Team (e.g., Mircea Greu at GSFC, Alessandro Battaglia at U. Leicester) to develop & evaluate combined radar-radiometer products.

Ongoing effort also at JPL



Summary

- RainCube: 1st spaceborne precipitation radar in a CubeSat
⇒ new observations of clouds & precipitation
- spaceborne C&P radars = CloudSat, GPM-DPR, RainCube
- Mission
 - ① prime mission ⇒ demonstrated radar capability
 - ② extended mission ⇒ validation of pointing & calibration using GPM, NexRAD, Reanalysis (ECMWF, MERRA)
 - ③ Continued extended mission ⇒ ↗ dataset for science studies to demonstrate value of combined observations

RainCube (radar in a *CubeSat*) cloud & precipitation profiling:
comparable performance to a *subset of GPM-DPR*

Full potential of RainCube technology hinges upon
deployment of multiple units in a (multiple) train(s)

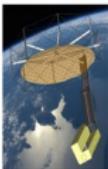
• Constellation of RainCube's "as is"

- Analyzing the current dataset to demonstrate the potential and the limitations of the current system in addressing science questions

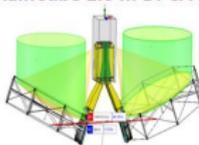
• Constellation with improved antennas & electronics

- To address a larger set of science questions
- Development of **technologies** and of **mission concepts** is ongoing
- Extension to W and G-band** for cloud & precip.
- DPCA** for Doppler, **Larger Size** for improved resolution and sensitivity, **multi-feed** for scanning

RainCube 1.0 m
in 12 U



RainCube 1.0 m DPCA in 24U



TENDEG

• Constellation with other Radars and Radiometers:

- A study team in the Earth Science Decadal Survey 2017 will consider RainCube-like constellations for measurements of convection and precipitation
- Higher frequency versions of RainCube for cloud and water vapor observations

• Planetary applications

- An evolution of this instrument could support altimetry and cloud and precipitation on planetary targets

RainCube : What's next ?

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Parameter	Current Baseline Estimate
Mass	141 kg
Power	200 W
Volume	3.0 m ³
Range	100 km
Beamwidth	100 km
Scan Rate	100 km
Resolution	100 km
Accuracy	100 km
Reliability	100 km
Availability	100 km

Ka-band ESTO InVEST and ACT programs

	6U	12 U	50 kg
Antenna size [m]	0.5	1.0	2.0
Sensitivity [dBZ]	15	5-10	0-5
Hor Resolution [km]	8	4	2
Range Res [m]	250		
Beams	1	1-3	1-5
RF Power [W]	10	10-20	10-40

Thank you!



Jet Propulsion Laboratory
California Institute of Technology

Data: <https://tcis.jpl.nasa.gov/data/raincube/>

Contacts: eva.peral@jpl.nasa.gov, simone.tanelli@jpl.nasa.gov,
eastwood.im@jpl.nasa.gov, ousmane.o.sy@jpl.nasa.gov

References:

- E. Peral et al., "Radar Technologies for Earth Remote Sensing From CubeSat Platforms," in *Proceedings of the IEEE*, vol. 106, no. 3, pp. 404-418, 2018
- N. Chahat et al., "CubeSat deployable Ka-band mesh reflector antenna development for earth science missions," in *IEEE TAP*, vol. 64, no. 6, pp. 2083-2093, 2016
- O.O. Sy et al., "Derived Observations From Frequently Sampled Microwave Measurements of Precipitation. Part II, in *IEEE TGRS*, vol. 55, no. 5, pp. 2898-2912, 2017
- G.L. Stephens et al., "A distributed small satellite approach for measuring convective transports in the Earth's atmosphere", in *IEEE TGRS*, early access, 2019